Ambulance Chasing Anomalous CDF $\mu\gamma$ Missing-E_T Events With Supersymmetry

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Abstract
CDF recently reported an excess of events in the $\mu\gamma$ missing E_T ($\not\!\!E_T$) channel that disagrees with the Standard Model prediction. No such excess was observed in the $e\gamma\not\!\!E_T$ channel. We explain the excess via resonant smuon production with a single dominant R-parity violating coupling λ'_{211}, in the context of models where the gravitino is the lightest supersymmetric particle. The slepton decays to the lightest neutralino and a muon followed by neutralino decaying to a gravitino and photon. We determine a viable region of parameter space that fits the kinematical distributions of the Run I excess and illustrate the effect by examining the best fit point in detail. We provide predictions for an excess in the $\not\!\!E_T$ and photon channel at Run I and Run II. Run II will decisively rule out or confirm the scenario. The work expounded here is published in [1, 2].

1. Introduction

CDF has recently presented results on the production of combinations involving at least one photon and one lepton (e or μ) in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, using 86 pb^{-1} of Tevatron 1994-95 data [3]. In general the results were consistent with the Standard Model (SM), however 16 photon-lepton events with large $\not\!\!E_T$ were observed, with 7.6 ± 0.7 expected. Moreover, 11 of these events involved muons (with 4.2 $\pm$ 0.5 expected) and only 5 electrons (with 3.4 $\pm$ 0.3 expected), suggestive of a lepton flavour violating asymmetry involving muons.

What can such a process be? A natural framework with explicit flavour violating couplings is provided by R-violating supersymmetry [4], which contains operators with a complicated flavour structure in the superpotential

$$W_{RPV} = \frac{1}{2}\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{1}{2}\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k + \mu_i L_i H_2 \qquad (1)$$

where L (Q) are the left-handed lepton (quark) superfields while $\bar{E}$, $\bar{D}$, and $\bar{U}$ contain the corresponding right-handed fields, and i, j, k generation indices. The second of the above terms is of particular interest, since it can lead to resonant slepton production in hadron-hadron collisions [5], via the diagram that appears in figure 1.

Such a resonance would lead to enhanced cross sections with a rich final state topology, which, as we are going to show, can explain the CDF anomaly. What would then be the structure of the associated operator? R-violating couplings have upper bounds coming from various

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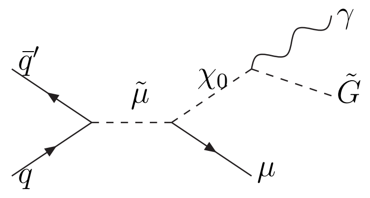

Fig. 1: Resonant smuon production and subsequent decay

flavour-violating processes [6]. Therefore, to get the requisite number of events to explain the observed anomaly, a sizable cross section is required which would then imply a process with valence quarks in the initial state. Since the events are seen in the muon channel, the operator can be specified to be $L_2 Q_1 \bar{D}_1$, which generates the couplings $\tilde{\mu} u \bar{d}$ and $\tilde{\nu}_\mu d \bar{d}$ (and charge conjugates), along with other supersymmetrised copies involving squarks. This coupling, λ'_{211}, is constrained from $R_\pi = \Gamma(\pi \to e\nu)/(\pi \to \mu\nu)$ [7] to be $< 0.059 \times \frac{m_{\tilde{d}_R}}{100 \text{ GeV}}$ [6].

Upon production, sleptons (in our case, smuons or sneutrinos) can in general decay via a large variety of channels [5] if they are kinematically accessible. However, the crucial observation is that R-violating supersymmetry by itself may not account for the observed anomaly, because of the fact that the anomaly is observed in a channel where a photon is produced. However, if the gravitino (present in all models where supersymmetry is gauged) is the lightest supersymmetric particle (LSP) it is too long-lived to decay within the detector [8]. Thus, the gravitino, $\tilde{G}$, provides the missing energy signature since it is electrically neutral and interacts rather weakly with matter. If the neutralino, as is often the case, is dominantly photino, then the decay $\chi_1^0 \to \tilde{G}\gamma$ can dominate [9]. It is interesting to note that the $ee\gamma\gamma\not{E}_T$ event recorded by CDF [10] can be explained by such a decay [11].

Since at the moment there is neither enhancement in the two-fermion final state, nor observation of chains of cascade decays, the most natural explanation is that the R-conserving decay mode of the smuon which produces the lightest neutralino dominates over the rest while subsequently $\chi_1^0 \to \tilde{G}\gamma$. The competing R-parity violating decay modes of $\chi_1^0 \to \nu jj$ and $\chi_1^0 \to \mu jj$ leading to $\mu jj\not{E}_T$ or $\mu\mu jj$ final states become negligible (as is the case here) when λ'_{211} and $m_{\tilde{G}}$ are both small enough. Smuon decay into two jets via the R-parity violating mode is essentially unobservable because of the huge 2 jet background. For example, for a resonance mass of 200 GeV, only a $\sigma.B > 1.3 \times 10^4$ pb is excluded at 95% C.L. [12]. This will not provide a restrictive bound upon our scenario.

It is worth stressing the clarity of the signatures, but also of future predictions in the case of a resonant process. Moreover, the presence of both slepton and sneutrino resonances are in principle to be expected, and we provide a prediction for $\gamma\not{E}_T$ events. The higher statistics in Run II of the Tevatron should allow verification our model.

The new aspect of the model we present here compared to previous studies of resonant slepton production at hadron colliders [5], is to marry the gravitino LSP scenario with R-parity violating supersymmetry. This marriage has been considered before in the context of dark matter [13].

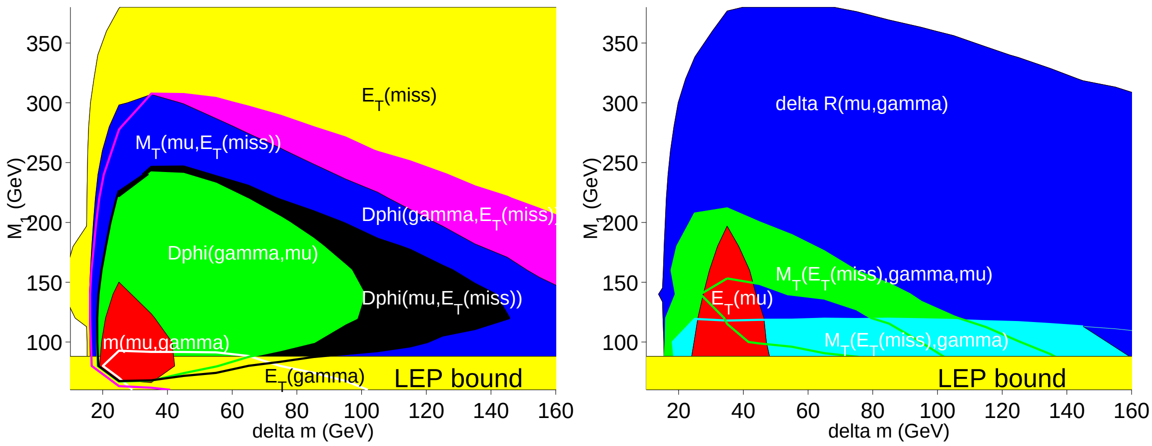

Fig. 2: Scans over M_1 and Δm. The 95% C.L. regions indicated by the fit to each kinematical distribution is shown.

2. Model and Results

We use the `ISASUSY` part of the `ISAJET7.58` package [14] to generate the spectrum, branching ratios and decays of the sparticles. For an example of parameters, we choose (in the notation used by ref. [14]) $\lambda'_{211} = 0.01$, $m_{3/2} = 10^{-3}$ eV, $\tan\beta = 10$, $A_{t,\tau,b} = 0$, and scan over the bino mass M_1 and the slepton mass $m_{\tilde{l}} \equiv m_{\tilde{L}_{1,2}} = m_{\tilde{e}_{1,2}}$ GeV. The values of λ'_{211} and $m_{3/2}$ are dictated by the need to have the decays shown in Fig. 1 being dominant. However, there are ranges of values in the R-violating coupling and the gravitino mass where this decay chain is obtained. In fact, the acceptable ranges are an order of magnitude in λ'_{211} and two orders of magnitude in $m_{3/2}$. μ together with other flavour diagonal soft supersymmetry breaking parameters are set to be so heavy that any superparticles except the first two generation sleptons, the lightest neutralino and the gravitino are too heavy to be produced or to contribute to cascade decays in Tevatron data. They therefore do not appear in this analysis. We have checked that this is true over a large volume of parameter space. We emphasise that this is a representative hyperplane in the supersymmetric parameter space and not a special choice.

We use `HERWIG6.3` [15] including parton showering (but not including isolation cuts) to calculate cross-sections for single slepton production. A γ-in-active-region cut requires that the photon *not* have rapidity $|\eta| > 1$ or $|\eta| < 0.05$. The region $0.77 < \eta < 1.0, 75° < \phi < 90°$ is also excluded because it is not instrumented. Fiducial photon detection efficiency was set to be 81%, whereas for the muons it is 66% for $1.0 > |\eta_\mu| > 0.6$ and 45% for $|\eta| < 0.6$. $\not{E}_T$ and the E_T of both the muon and photon were required to be greater than 25 GeV.

We calculate the difference in log likelihood between our model and the SM given by each kinematical variable that was presented in ref. [3]. This provides 95% C.L. limits upon M_1 and $\Delta m = m_{\tilde{l}} - M_1$. We show the viable regions for the energy distributions: $E_T(\gamma,\mu)$, $\not{E}_T$, the mass m and transverse mass M_T distributions $m_{\mu\gamma}$, $M_T(\mu\not{E}_T)$, $M_T(\not{E}_T\gamma)$, $M_T(\gamma\mu\not{E}_T)$ and various transverse angular separations $\Delta\phi_{ij}$, where $i,j = \mu,\gamma,\not{E}_T$. ΔR, defined as the distance in $\eta - \phi$ space between the muon and the photon, is also used. It is not possible to take correlations between these different kinematical variables into account because we do not possess the multi-dimensional data. Therefore we resort to examining each one in turn and see to what extent each region overlaps. Fig. 2 shows that all of the 95% confidence level regions

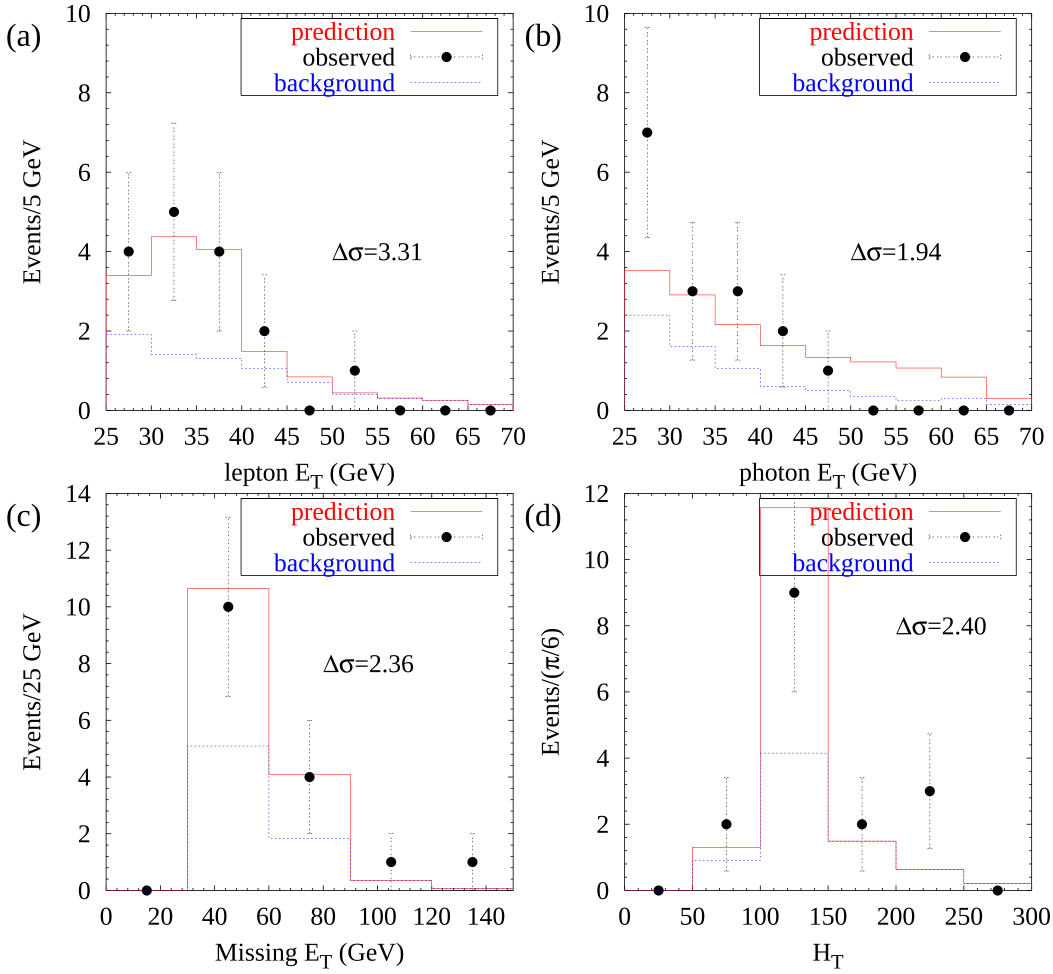

Fig. 3: Energy distributions for the lepton $\gamma\not{E}_T$ events. We show the distributions in (a) lepton E_T, (b) photon E_T, (c) $\not{E}_T$ and (d) H_T=$E_T(\gamma)+\not{E}_T+E_T(\gamma)$. The solid red histogram is signal plus background for our best-fit point, the blue dashed histogram is the Standard Model background and the black points (with $\sqrt{N}$ error-bars imposed) are the observed number of events. $\Delta\sigma$ is the difference in χ^2 between the Standard Model prediction and the best-fit point for the relevant distribution.

overlap at $M_1 \approx 90$ GeV, $\Delta m = 25 - 40$ GeV, indicating that our model is in good agreement with all of the observed kinematical properties of the events. The region at the bottom the plots is ruled out by LEP2 from neutralino pair production [16].

The most discriminating kinematical variable is $E_T(\mu)$, which prefers our model over the SM at the 3.3σ level at the best fit point $M_1 = 87$ GeV and $\Delta m = 35$ GeV. We refer to this point as "the best fit point" from now on, and examine its properties more closely.

We show the predicted energy distributions in Fig. 3 at the best-fit point and compare them with the data and the SM background in the *lepton* $\gamma\not{E}_T$ sample[1]. The figure shows that the energy distributions are in broad agreement with the best-fit point model. Other kinematical properties are also well-fit [2]. Important features of the sparticle spectrum are displayed in

[1]We use this sample rather than $\mu\gamma\not{E}_T$ because it was the one selected *a priori* for study by CDF.

Table 1: MSSM spectrum used to explain anomalous events at the best fit point within the acceptable fit range for $m_{\tilde{G}} = 10^{-3}$ eV, $\tan\beta = 10$ and $\lambda'_{211} = 0.01$. We have displayed the relevant sparticle masses. All other sparticles are heavier than 1900 GeV, and thus do not interfere with our analysis.

particle	$\tilde{e}_L$,$\tilde{\mu}_L$	$\tilde{\nu}_e$,$\tilde{\nu}_\mu$	χ_1^0	$\tilde{\mu}_R$,$\tilde{e}_R$
best-fit mass	131 GeV	104 GeV	87 GeV	130 GeV
range	121–162 GeV	92–141 GeV	87–120 GeV	120–161 GeV

Table 2: Percentage of SUSY events for the best fit point that satisfy cumulative cuts for $\mu\gamma\not{E}_T$ events at CDF, Run I. Events that pass a cut in a given entry also pass those cuts with a larger percentage.

cut	percentage
fiducial muon efficiency	52.2
$\not{E}_T > 25$ GeV	41.6
$E_T(\gamma) > 25$ GeV	33.9
γ detected	20.8
$E_T(\mu) > 25$ GeV	15.3
$\lvert\eta_\mu\rvert < 1.0$	11.4

Table 1. We also show the range of sparticle masses corresponding to the acceptable fit range of parameter space. The acceptable fit range is defined as being compatible with at least all but one of the 95% C.L. regions in fig 2. The relevant branching ratios of the smuon are

$$BR(\tilde{\mu}_L \to \chi_1^0 \mu) = 0.984, \qquad BR(\tilde{\mu}_L \to \bar{u}d) = 0.015, \qquad BR(\tilde{\mu}_L \to \tilde{\mu}\tilde{G}) = 0.001, \quad (2)$$

with a lifetime of 1×10^{-23} sec, whereas for the lightest neutralino we have

$$BR(\chi_1^0 \to \tilde{G}\gamma) = 0.975, \qquad BR(\chi_1^0 \to \tilde{G}e^- e^+) = 0.020, \quad (3)$$

with a lifetime of 1×10^{-19} sec. At such small values of λ'_{211} and $m_{\tilde{G}}$, R-parity violating decays of the lightest neutralino are negligible. In Table 2, we show the percentage of events making it through each of the cuts. The table shows that 11.4% of the smuons produced end up as detected $\mu\gamma\not{E}_T$ events in CDF. The corrected cross-section of 0.091 pb corresponds to 7.8 events additional to the 4.2±0.5 predicted by the SM for 86 pb^{-1} of luminosity, adequately fitting the excess of events quoted by CDF at Run I.

We now determine the rate of single sneutrino production at Run I. The process is: $\tilde{\nu} \to \nu\chi_1^0$ followed by $\chi_1^0 \to \tilde{G}\gamma$. This would appear to mimic $Z\gamma$ production, where $Z \to \nu\bar{\nu}$. To compute the cross-section for this process, we use the cuts used by the D0 experiment in their $\gamma\not{E}_T$ analysis [17]. With their cuts, we predict a supersymmetric cross-section of 0.054 pb for the $\not{E}_T\gamma$ process at the Run I energy, which corresponds to about 0.7 events for the 14 pb^{-1} data analyzed by the D0 experiment. The D0 experiment observed 4 events over a SM background of 1.8±0.2 events but with a much bigger background coming from cosmic ray sources which is estimated to be 5.8±1.0. As far as we are aware, the analysis has not yet been done with the full Run I Tevatron data but we would expect about 5.4 events for a 100 pb^{-1} data sample. CDF recently performed such an analysis [18], the results of which will be included in a fit in a forthcoming publication [19]. We will also include a D0 analysis of $W\gamma$ production [20].

We perform the above analyzes for Run II (at $\sqrt{s} = 2$ TeV) for the best fit point in order to make predictions for observable supersymmetric cross sections:

$$\sigma(\gamma\mu\not{E}_T) = 0.098 \text{ pb}, \qquad \sigma(\gamma\not{E}_T) = 0.36 \text{ pb}, \tag{4}$$

which, ought to be observable with good statistics. Since we do not the numbers for the cuts and the efficiencies at Run II, we have simply used those that the CDF experiment used in their $\mu\gamma\not{E}_T$ analysis at Run I. To that extent, these numbers are only indicative. For example, with an integrated luminosity of 2 fb^{-1}, these cross-sections would correspond to 195 and 720 events, respectively. We predict 0.8 expected selectron pairs at Run I. Thus, the discrepancy with respect to the SM [10] from the observation of an $ee\gamma\gamma\not{E}_T$ event in the Run I data is vastly ameliorated. R-parity conserving production processes such as these will be observable at Run II providing more independent checks upon our scenario. One expects an identical number of smuon pairs, leading to a $\mu\mu\gamma\gamma\not{E}_T$ final-state. This final state has not yet been observed by CDF, but we note that combining the $ee\gamma\gamma\not{E}_T$ and $\mu\mu\gamma\gamma\not{E}_T$ channels, our model still vastly ameliorates the discrepancy with respect to the SM.

3. Conclusions

We have demonstrated that R-parity violating supersymmetry with a light gravitino can explain an anomalously high measured cross-section for the $\mu\gamma\not{E}_T$ channel. We have provided possible tests for this hypothesis, in the form of SUSY cross-sections for the $\gamma\not{E}_T$ channel, and predictions for the cross-sections of both channels at Run II of the Tevatron collider. The $\gamma\not{E}_T$ channel looks particularly promising because it will allow an independent check of our scenario.

Another interesting question to ask is whether the signal can also be obtained from a specific model of supersymmetry breaking, such as gauge mediated supersymmetry breaking, consistent with all other data [21].

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